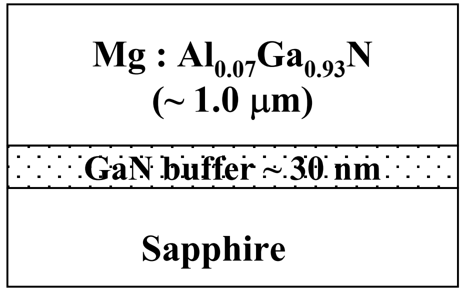
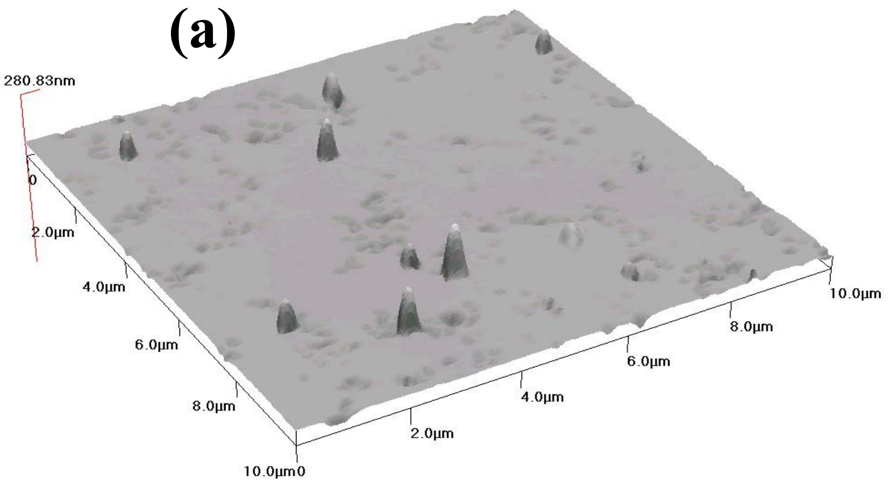
AFM Images of (a) Mg-δ-Doped and (b) Uniformly Mg-doped p-Type AlGaN

after ICP etching - 0.5 μm removed

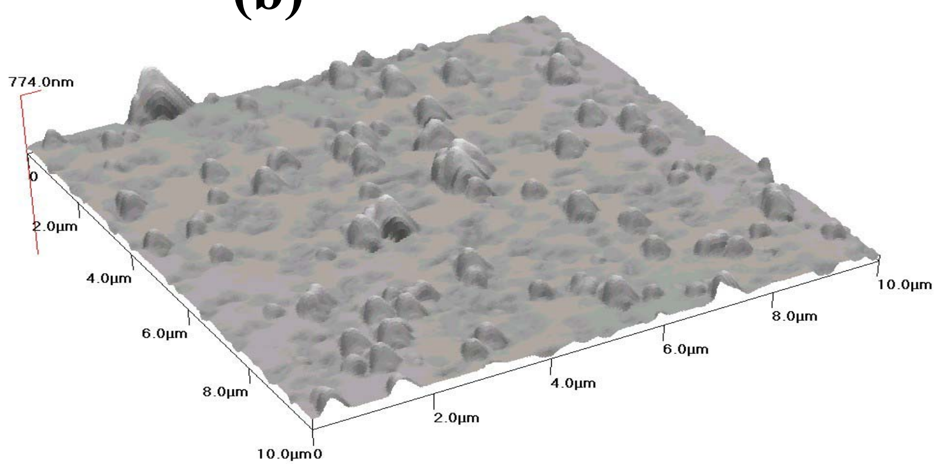


(a)



δ-doped, etch pit density 0.9 x 10^7 /cm^2

(b)



uniformly doped, etch pit density 7.9 x 10^7 /cm^2

AFM morphologies of etched surfaces of (a) Mg-δ-doped p-type AlGaN epilayer after a 0.5 μm removal by dry etching and (b) uniformly Mg-doped p-type AlGaN epilayer after a 0.5 μm removal by dry etching. AFM images reveal that the etch pit density (and hence the dislocation density) was significantly reduced in Mg-δ-doped p-type AlGaN compared with uniformly Mg-doped p-type AlGaN.

δ-doping for Enhanced P-type Conduction in GaN and $Al_xGa_{1-x}N$ Alloys; Jingyu Lin & Hongxing Jiang - Kansas State University (DMR-9902431).

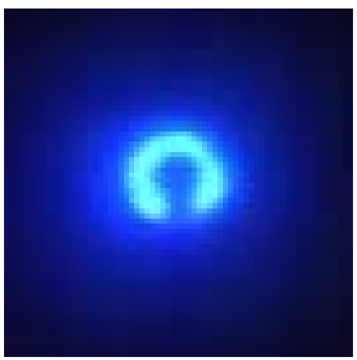
Currently there is a great need of solid-state ultraviolet (UV) emitters for chem-bio-agent detections as well as for next generation lighting. In such applications, p-type conductive AlGaN alloys with relatively high Al contents are indispensable for hole injection. Due to the deepening of the Mg acceptor activation energy as well as reduced crystalline quality of the AlGaN alloys with increasing Al content, however it is difficult to achieve p-type AlGaN with relatively high Al contents.

Recently Hongxing Jiang & Jingyu Lin's group has achieved a hole concentration of about 1 x 10^{17} cm^{-3} and mobility 7 cm^2/VS at room temperature in Mg doped $Al_{0.27}Ga_{0.73}N$ epilayers, as confirmed by Hall measurements [Appl. Phys. Lett. 80, 1210 (2002)]. Prior to this, p-type conduction was only demonstrated in $Al_xGa_{1-x}N$ epilayers for x up to 0.15. The group employed Mg δ-doping and demonstrated that δ-doping significantly suppresses the dislocation density, enhances the p-type conduction, and reduces the non-radiative recombination centers in GaN and AlGaN. A δ-junction-like doping profile was implemented by interrupting the usual crystal-growth mode by closing the Ga flow and leaving the N flow continuously. The N-stabilized crystal surface was thus maintained while the Mg impurities were introduced to the growth chamber, so that an impurity-growth mode results. In this mode the host crystal does not continue to grow and Mg impurities could occupy a small fraction of available Ga or Al sites in the δ-doped plane, typically $^1/_{10}$ to $^1/_{10000}$. This reduced Mg impurity self-compensation and enhanced hole concentrations in Mg-δ-doped GaN or AlGaN. The δ-doping technique represents the ultimate control of a dopant profile and it will play an increasingly important role in future nitride electronic and photonic devices.

By incorporating these p-type $Al_{0.27}Ga_{0.73}N$ layers into the emitter structures, the group has demonstrated the operation of 340 nm UV light emitting diodes (LED). The development of solid-state UV emitters based on III-nitrides would allow fluorescence detection of biological threats. On the other hand, the current approach for generating white light is by coating the III-nitride blue LED chips with yellow or green phosphor. This approach however suffers from severe color rendering and low power conversion efficiency problems. These problems can be greatly minimized by employing UV LEDs together with three-color phosphors for wavelength down conversion. If all household lights were replaced by white LEDs, about $100 billion in energy costs a year could be saved worldwide, in addition to significant decreases in pollution.

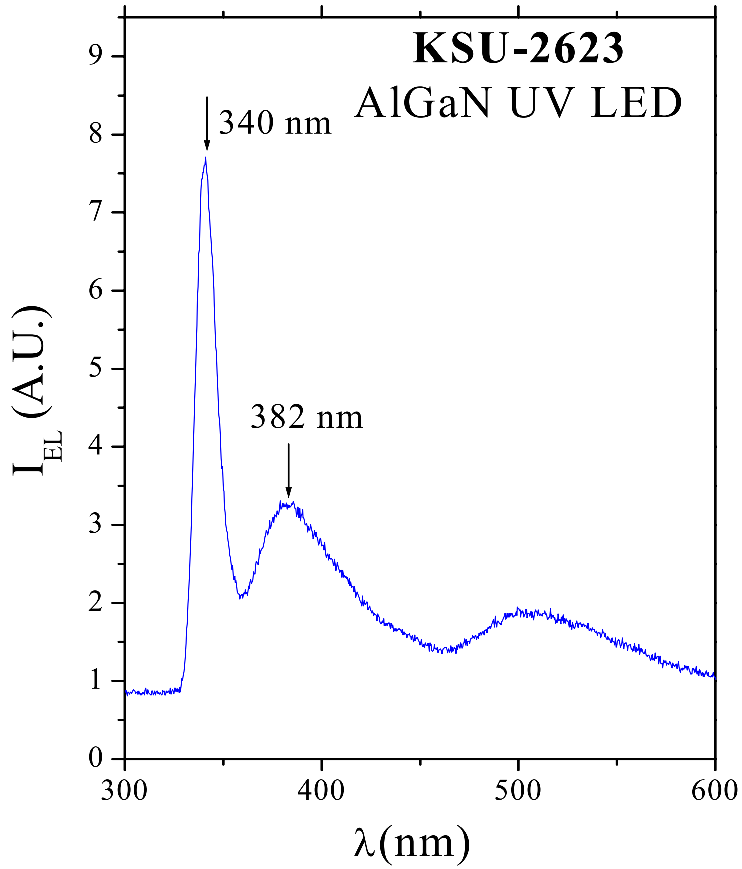
KSU UV μ-LED (λ=340 nm)

d=15 μm



d=12 μm

AlGaN UV μ-LED in action.



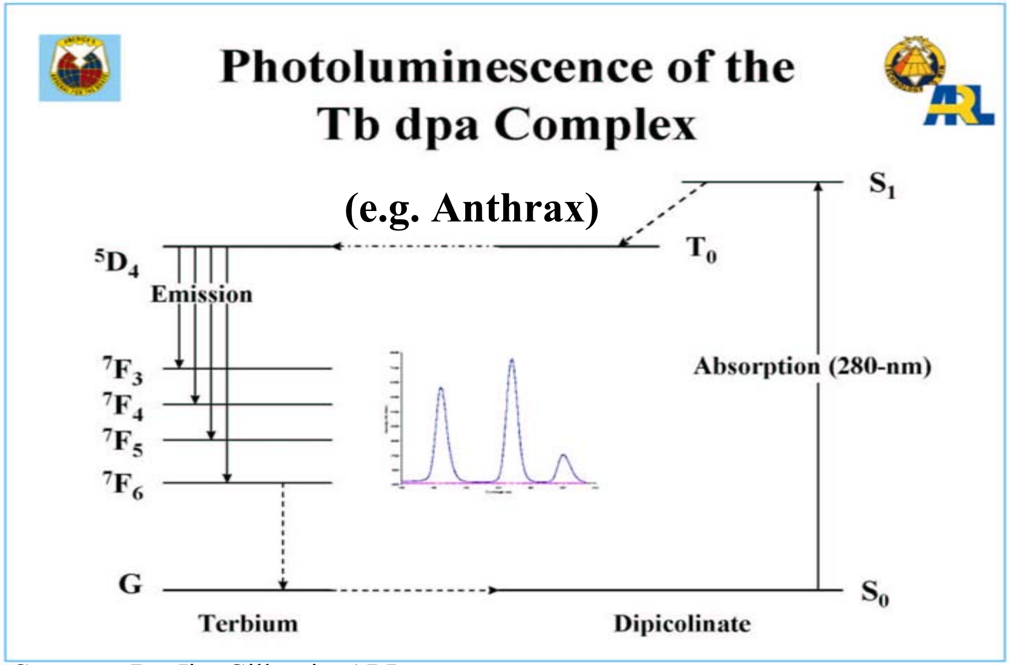
Electroluminescence spectrum of KSU UV LEDs.

Micro-Size III-Nitride UV Light Emitters; Jingyu Lin & Hongxing Jiang - Kansas State University (DMR-9902431).

Recently Jiang/Lin's group has successfully fabricated UV (340 nm) micro-size light emitting diodes (LEDs) and arrays based on AlGaN/AlGaN quantum wells. To fabricate these micro-size LEDs, sapphire substrates with 30 nm AlN buffer layers were used to grow QW device layers (a 0.5 micron of Si-doped n-type $Al_{0.2}Ga_{0.8}N$ Ohmic contact layer, 0.5 micron of silicon doped n-type superlattice consisting alternating layers of 50 Å/50 Å of $AlN/Al_{0.2}Ga_{0.8}N$, a 1.0 micron silicon doped n-type $Al_{0.2}Ga_{0.8}N$, a 20 Å undoped $Al_{0.1}Ga_{0.9}N$ active quantum well, a 30 Å of undoped $Al_{0.2}Ga_{0.8}N$ barrier, a 7 nm of Mg doped p-type $Al_{0.27}Ga_{0.73}N$ blocking layer, 0.2 micron superlattice consisting alternating layers of 50 Å /50 Å of $AlN/Al_{0.2}Ga_{0.8}N$, and 0.1 micron Mg-doped GaN p-Ohmic contact layer, followed by a rapid thermal anneal at 950 °C for 5 seconds in nitrogen. The incorporation of the p-type AlN/AlGaN superlattice structure is to further enhance the p-type conduction, while the insertion of the p-type $Al_{0.27}Ga_{0.73}N$ blocking layer is to ensure the hole injection and confinement in the well region. Arrays of micro-size UV LEDs with individual disk diameter of about 10 microns were then fabricated from the AlGaN/AlGaN QW LED wafers by photolithography patterning, inductively coupled plasma dry etching, and Ohmic contact metallization. It was found that the problems associated with conventional broad-area UV emitters, such as poor current spreading and extraction efficiency, were significantly reduced in micro-size UV emitters.

The development of micro-size solid-state UV emitter arrays based on III-nitrides would allow chip-scale integration of Chem/Bio sensors for detection of chemical or biological threats. Other applications include pre-cancer cells detection with compact UV source in medical and health. Protein fluorescence is generally excited by UV light sources and changes in intrinsic fluorescence can be used to monitor structural changes in a protein. The availability of chip-scale UV light sources may open new avenues for medical research.

III-Nitride UV Light Emitters – Biological Agent Detection



Courtesy: Dr. Jim Gillespie, ARL

To achieve deep UV semiconductor optical sources (λ ~280 nm) based on III-nitrides, both p-$Al_xGa_{1-x}N$ and n-$Al_xGa_{1-x}N$ (x ~0.6) are needed for carrier injection and confinement.

Highly Conductive n-type Al_xGa_{1-x} N Alloys (x up to 0.7) Have Been Achieved
Si-Dopant Concentration $N_{Si} = 5 \times 10^{18}$ cm $^{-3}$

x	0.5	0.6	0.65	0.7
	KSU-A597	KSU-A595	KSU-A594	KSU-A599
$\sigma(\Omega\text{-cm})^{-1}$	8.3	6.7	6.7	2.2
$\mu(cm^2/Vs)$	33.6	30	20	21
$n(cm^{-3})$	1.44×10^{18}	1.9×10^{18}	2.1×10^{18}	6.2×10^{17}

Defeating High Resistivity of $Al_xGa_{1-x}N$ Alloys with High Al Contents; Jingyu Lin & Hongxing Jiang - Kansas State University (DMR-9902431).

Currently there is a great need of solid-state ultraviolet (UV) emitters for chem-bio-agent detections. In such applications, UV emitters with wavelength shorter than 300 nm are also needed. For example, protein/bio-agent fluorescence is generally excited at 280 nm or 340 nm. Although many of the ideas and potentials of III-nitride semiconductors for UV applications have been identified, a transition from basic research to practical device components has not yet been made. Achieving highly conductive n-type $Al_xGa_{1-x}N$ alloys with high Al contents remains one of the foremost challenging tasks of the Nitride community, since highly conductive n-type $Al_xGa_{1-x}N$ alloys with Al contents (x) as high as 0.6 - 0.7 are needed in 280 nm UV emitters.

Recently, Hongxing Jiang & Jingyu Lin's group has achieved highly conductive n-type $Al_xGa_{1-x}N$ for x as high as 0.7 (a resistivity value as low as 0.15 ohm-cm has been achieved). Prior to this, only insulating $Al_xGa_{1-x}N$ ($x > 0.5$) can be obtained. Our success is largely attributed to our unique capability for monitoring the optical qualities of these layers - the development of the world's first (and presently only) deep UV picosecond time-resolved optical spectroscopy system for probing the optical properties of III-nitrides [photoluminescence (PL), electro-luminescence (EL), etc.] with a time-resolution of a few ps and wavelength down to deep UV (down to 195 nm). Our time-resolved PL results have shown that we must fill in the localization states (caused by alloy fluctuation) by doping before conduction could occur. The density of states of localization states is about 10^{18} /cm^3 in this system [Appl. Phys. Lett. accepted]. The NSF supported research has laid the groundwork for achieving 280 nm UV emitters. However, obtaining p-type AlGaN alloys with high Al contents is still a great challenge. Novel doping methods must be further developed.

Jingyu Lin & Hongxing Jiang - Kansas State University (DMR-9902431).

Prof. Lin works with girls in the GROW workshop.

The P.I. (Lin) of this project serves as a faculty advisor for the Woman in Engineering and Science Program (WESP) at Kansas State University. WESP provides outreach, recruitment, and programs for girls and woman from middle school through post-graduate levels, to encourage them to consider and persist in careers in science, mathematics and engineering. WESP has helped to conduct an NSF supported Girls Researching Our World (GROW) workshop, which is targeted for 7 and 8th grade girls. In June 2001, Professor Lin (together with a female physics graduate student) has developed a 2-hour hands–on working activities dealing with "Light and Colors," within which topics dealing with semiconductor photonics materials and devices (LEDs and lasers) were embedded. The approaches were quite successful. New activities involving semiconductor materials and photonic devices will be further developed for these girls.

This summer, our lab is scheduled to host two workshops for secondary students: One on June 5 & 11, 2002 – Gear-up workshop, a program designed for the 9th grade students; one on the week of June 17 – GROW workshop. Currently, many young people simply do not know that careers such as materials scientists and photonics or optical engineers exist for woman or even understand the importance of materials sciences and semiconductor devices in their daily lives. However, advances in areas of semiconductor photonics will ultimately have a profound effect on how we learn, work, communicate, and live. We believe that research programs such as ours in the state of Kansas can help to enhance this awareness.

Diversity and International Cooperation at the Forefront Research in Advanced Semiconductors; Jingyu Lin & Hongxing Jiang - Kansas State University (DMR-9902431). Jiang/Lin's group at is at the forefront research effort involving the III-nitride wide bandgap semiconductors, which have emerged as the most important optoelectronic material system. The program is a well-integrated and multi-faceted one, ranging from materials synthesis by the state-of-the-art epitaxy, novel structure and device processing by nano-fabrication technologies, and material and device characterization and physical property measurements by nano-scale optical, electrical and structural probes. Students and postdoctoral researchers in the group have seven different nationalities (USA, China, Korea, Nepal, India, Pakistan, and Uganda), providing a truly international and multicultural working environment. Supported by the NSF grant are Postdoctoral Researcher Dr. Tom Oder (a black physicist), graduate student Ki-Bum Nam (from Korea), and undergraduate student Chris Wyant (from Kansas, USA). Ms. Lun Dai (a visiting graduate student from Peking University) was supported in part by an international cooperative grant through the NSF's Division of International Programs. The Korea Research Foundation supported Visiting Professor Hyeon Kim. Other group members are supported by grants from Department of Energy and Department of Defense. Research programs of interdisciplinary nature, such as this one, would not only attract students into the science and engineering areas, but can also better train students to compete successfully in today's challenging technological world.